

Snow line localization in classical protoplanetary disks

Sandra Blevins^{1,2}, Klaus Pontoppidan², Andrea Banzatti², Ke Zhang³, Colette Salyk⁴, Geoff Blake³

¹Catholic University of America, ²STScI, ³Caltech, ⁴NOAO

Introduction

Protoplanetary disks surrounding young solar-type stars are rich in gas and dust. An important component of disks are volatiles, loosely defined as molecular and atomic species with low sublimation★ temperatures ($T \leq 150$ K). Volatiles dominate the mass budget of condensible molecules. That is, there is typically about twice as much ice as rock in cold regions of the disk. The most common species include water, CO, CO₂ and various organics (Najita et al. 2003; Lahuis et al. 2006; Carr and Najita 2008; Salyk et al. 2011; Pascucci et al. 2013). Each species condenses out of the gas phase at its own specific sublimation temperature, leading to the emergence of "snow lines". **Snow lines are curves demarcating the phase transition between ice and gas of a specific volatile, and their shape depend both on the distance to the central star and the depth into the disk.**

Ices in disks are important because they, as a major solid mass reservoir, drive the formation of planetary cores and planetesimals. The location of the snow lines also define where volatiles can be delivered, potentially where habitable planets originally form. In this work, we are focusing on water, which is the most abundant ice in disks and define the "classical" snow line. The snow lines are dynamic and evolve with the disk and the central star. Locating snow line radii enables us to link the amount of material available for planet formation to the evolutionary stage of the disk.

Objective

The snow line of CO has recently been imaged by ALMA (Qi et al. 2013, Science) in one disk at around 50 AU. Our goal is to measure the location of the classical water snow line at a few AU in the surfaces of four classical protoplanetary disks around solar-mass young stars. The four disks have been selected to show strong emission from warm water vapor at mid-infrared wavelengths (10-40 micron).

★ sublimation: transitions directly from solid to gas

Results

RNO 90: a young, solar analog

Figure 1 : Variations of free parameters and their affect on the multi-wavelength model spectrum. Top row: The snow line is varied by one value in parameter space; the inner and outer water abundances remain constant. Middle row: Only the outer water abundances are varied. Bottom row: Only the inner water abundances are varied. Columns: the step function/abundance structure, proceeded by high to low excitation water lines.

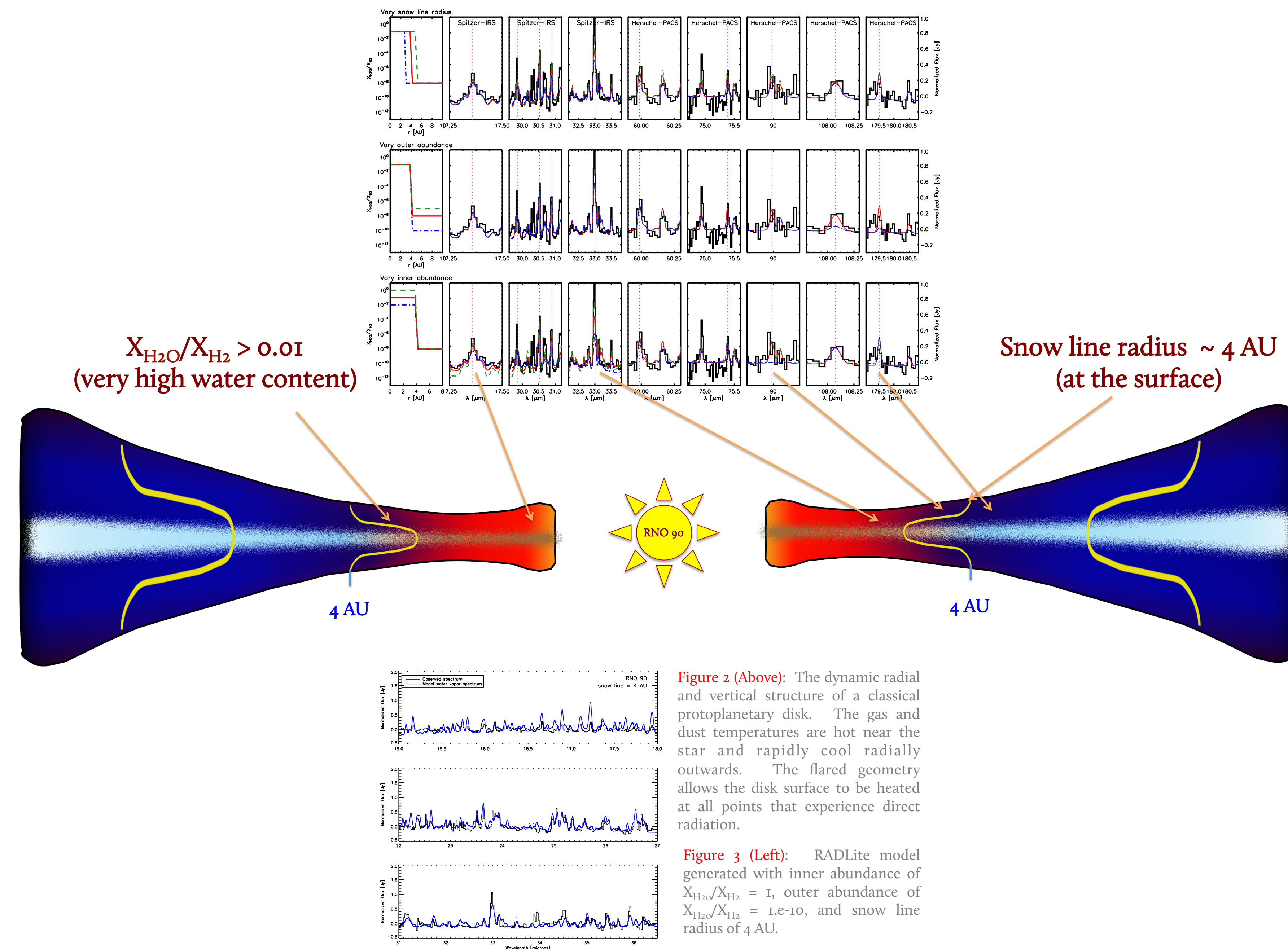


Figure 2 (Above): The dynamic radial and vertical structure of a classical protoplanetary disk. The gas and dust temperatures are hot near the star and rapidly cool radially outwards. The flared geometry allows the disk surface to be heated at all points that experience direct radiation.

Figure 3 (Left): RADLite model generated with inner abundance of $X_{H_2O}/X_{H_2} = 1$, outer abundance of $X_{H_2O}/X_{H_2} = 1 \times 10^{-10}$, and snow line radius of 4 AU.

Discussion and conclusions

In general, we find surface snow lines around 4 AU, consistent with our radiative transfer models of externally irradiated disks. The apparent high abundance of water vapor in the inner disk is larger than what can be naturally explained by gas-phase chemistry (Najita et al. 2011). We speculate that this is evidence of large scale migration of icy bodies as predicted theoretically by Ciesla & Cuzzi 2006. Further, planetary cores potentially forming within the snow line are bathed in gas with very high abundances of water vapor, allowing for some water delivery through direct gas accretion (Chiang & Laughlin 2013).

Data and modeling strategy

- 1) Use archival Spitzer-IRS and new, deep Herschel-PACS spectroscopy to measure the amount of emitting water at different temperatures.
- 2) Use a two-dimensional radiative transfer model to localize gas temperatures as a function of disk radius, thereby constructing a radial map of water vapor emission.
- 3) Compare the measured locations of the water snow lines to evolutionary models of protoplanetary disks to inform models of planet formation and volatile delivery to habitable planets.

Results

We find that the higher excitation Spitzer lines are particularly sensitive to the water abundance in the inner disk, while the lower excitation Herschel lines are sensitive to the abundance of water vapor beyond the snow line (see also Hogerheijde et al. 2011, Science). However, the combination of both Spitzer and Herschel lines is critical for determining the radius of the snow line. In Figure 1, we present a detailed model fit to one of our sample disks, RNO 90, which is one of the strongest water emitters known.

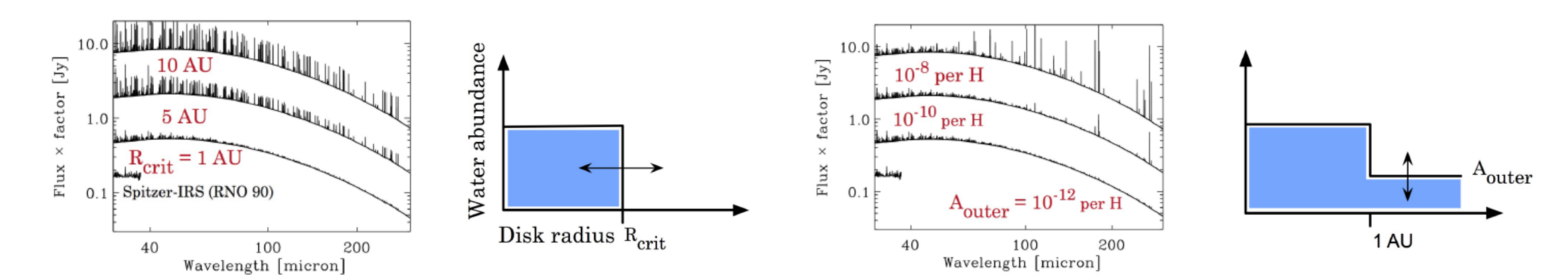


Figure 4 : Sensitivity of high and low energy water transitions and how they help constrain the snow line radius.

References

- (1) Najita et al. 2003, ApJ, 589, 931 (2) Lahuis et al. 2006, ApJ, 636, L145 (3) Carr & Najita 2008, Science, 319, 1504 (4) Salyk et al. 2008, ApJ, 676, L49 (5) Salyk et al. 2011, ApJ, 731, 130 (6) Pascucci et al. 2013, ApJ, 779, 178 (7) Ida & Lin 2004, ApJ, 604, 388 (8) Johansen et al. 2007, Nature, 448, 1022 (9) Qi et al. 2013, Science, 341, 630 (10) Pontoppidan et al. 2009, ApJ, 704, 1482 (11) Pontoppidan et al. 2010, ApJ, 720, 887 (12) Najita et al. 2011, ApJ, 743, 147 (13) Ciesla & Cuzzi 2006, Icarus, 181, 178 (14) Chiang & Laughlin 2013, MNRAS, 431, 3444 (15) Hogerheijde et al. 2011, Science, 334, 338